An Autonomous Diagnostic and Prognostic Monitoring System for NASA's Deep Space Network

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Abstract—Our objective is to provide a framework of automated tools and techniques for reducing operational and maintenance costs in the NASA's Deep Space Network (DSN). The focus of our technology application is fault diagnostics and prognostics for ground systems during DSN tracking operations. The domain chosen to demonstrate our capability is the new DSN Full Spectrum Processing Array configuration located at the Goldstone Deep Space Communications Complex (GDSCC) which is monitored by the Jet Propulsion Laboratory (JPL).

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1. INTRODUCTION

Our objective is to provide a framework of automated tools and techniques for reducing operational and maintenance costs in the NASA's Deep Space Network (DSN). The focus of our technology application is fault diagnostics and prognostics for ground systems during DSN tracking operations. The domain chosen to demonstrate our capability is the new DSN Full Spectrum Processing Array configuration located at the Goldstone Deep Space Communications Complex (GDSCC) which is monitored by the Jet Propulsion Laboratory (JPL).

To accomplish our goals we use two JPL developed tools: Beacon-based Exception Analysis for Multi-missions (BEAM) and Spacecraft Health Inference Engine (SHINE). BEAM is used as a highly advanced prognostic state estimator and SHINE is being used for hard real-time diagnostics and interpretation of the system state output by BEAM. These technologies provide new insights into system visibility that were not previously possible using channel-based diagnostics techniques thereby making near zero false alarms attainable. Raw sensor data and software-derived data are simultaneously fused in real-time to automatically abstract system physics and information invariants (constants). This methodology enables a system to be ultra-sensitive to degradation and changes, and to isolate significant events in both time and space to specific sensors.

This paper provides an overview of the synergistic approach to applying BEAM and SHINE technologies to DSN ground tracking systems, which maximizes the benefits from each of these technologies.

2. BACKGROUND

Automation of DSN downlink operations is a critical step in the advancement of NASA's communication link to future unmanned spacecraft. The forces behind the development of autonomous ground systems are both economic and technical. The era of NASA's New Millenium, Discovery and Mars Exploration programs will result in a series of "faster, better, cheaper" missions. These new mission series will approximately triple the mission load for DSN operations, thereby, increasing the demand for reliable and efficient ground tracking systems with minimum system failures and minimum downtime. An increase in operations staff would result in prohibitive costs and in a non-optimal solution. Furthermore, as the complexity of multi-mission tracking increases and the amount of data increases, human operators are less able to cope with real-time fault handling. The alternative is automation.

JPL's Telecommunications and Missions Operations Directorate (TMOD) has recognized the above and is funding research of autonomous diagnostic systems for use in the DSN. One such research task is the Fault Detection, Isolation and Recovery (FDIR) automation task. This task has successfully created an infrastructure that utilizes BEAM and SHINE technologies to address the FDI components. The result is a prototype of an autonomous diagnostic and prognostic monitoring system for DSN operations.

DEEP SPACE NETWORK

The NASA Deep Space Network (DSN) is an international network of antennas that supports interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and the universe. The network also supports selected Earth-orbiting missions.

The DSN currently consists of three deep-space communications facilities placed approximately 120 degrees apart around the world: at Goldstone, in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. This strategic placement permits constant observation of spacecraft as the Earth rotates, and helps to make the DSN the largest and most sensitive scientific telecommunications system in the world.

NASA's scientific investigation of the Solar System is being accomplished mainly through the use of unmanned automated spacecraft. The DSN provides the vital two-way communications link that guides and controls these planetary explorers, and brings back the images and new scientific information they collect. All DSN antennas are steerable, high-gain, parabolic reflector antennas.

The antennas and data delivery systems make it possible to:

- Acquire telemetry data from spacecraft.
- Transmit commands to spacecraft.
- Track spacecraft position and velocity.
- Perform very-long-baseline interferometer observations.
- Measure variations in radio waves for radio science experiments.
- Gather science data.
- Monitor and control the performance of the network.

OBJECTIVE

Our objective is to develop a system of integrated analytical and artificial intelligent methods that provides an autonomous and optimal solution for FDI decision-making in the DSN operational environment. Previous attempts have focused on neural-net based systems that require large amounts of DSN training data and a priori knowledge of sensor data. Our system uses BEAM technology to not only process inputs currently used by human experts who perform diagnostics, but also to process all DSN data which is needed to achieve complete fault diagnostics and prognostics at every level of operations. In addition to our FDI-BEAM application, we have developed a SHINE-based expert system that performs both model-based reasoning and case-based reasoning. The expert system has proved successful in exercising and validating heuristic knowledge using real-time DSN data.

The innovation of our approach is the synergy of BEAM's ability to provide complex DSN system analysis using stochastic modeling, nonlinear information filtering, temporal channel analysis and adaptive wavelet theory, with SHINE's high speed inferencing capability in a real-time continuous environment. We have packaged this technology as a DSN subsystem that is compatible with the new DSN monitor and control protocol.

DSN AUTONOMOUS FDI FRAMEWORK

The goal of the FDI framework that we have built is to provide a DSN-compatible infrastructure that provides seamless integration of heterogeneous, intelligent tools for the purpose of DSN FDI analysis. The target domain for our prototype is the DSN antenna array configuration. It is depicted in Figure 1. This framework has been packaged as a DSN subsystem which interfaces with the DSN's new Network, Monitor and Control (NMC) computing environment (Figure 2). The FDI Subsystem includes three components: 1) FDI Server; 2) SHINE-based Expert System; and 3) FDI-BEAM client application. The components are integrated into a tightly coupled architecture composed of a number of analysis components (Figure 3).

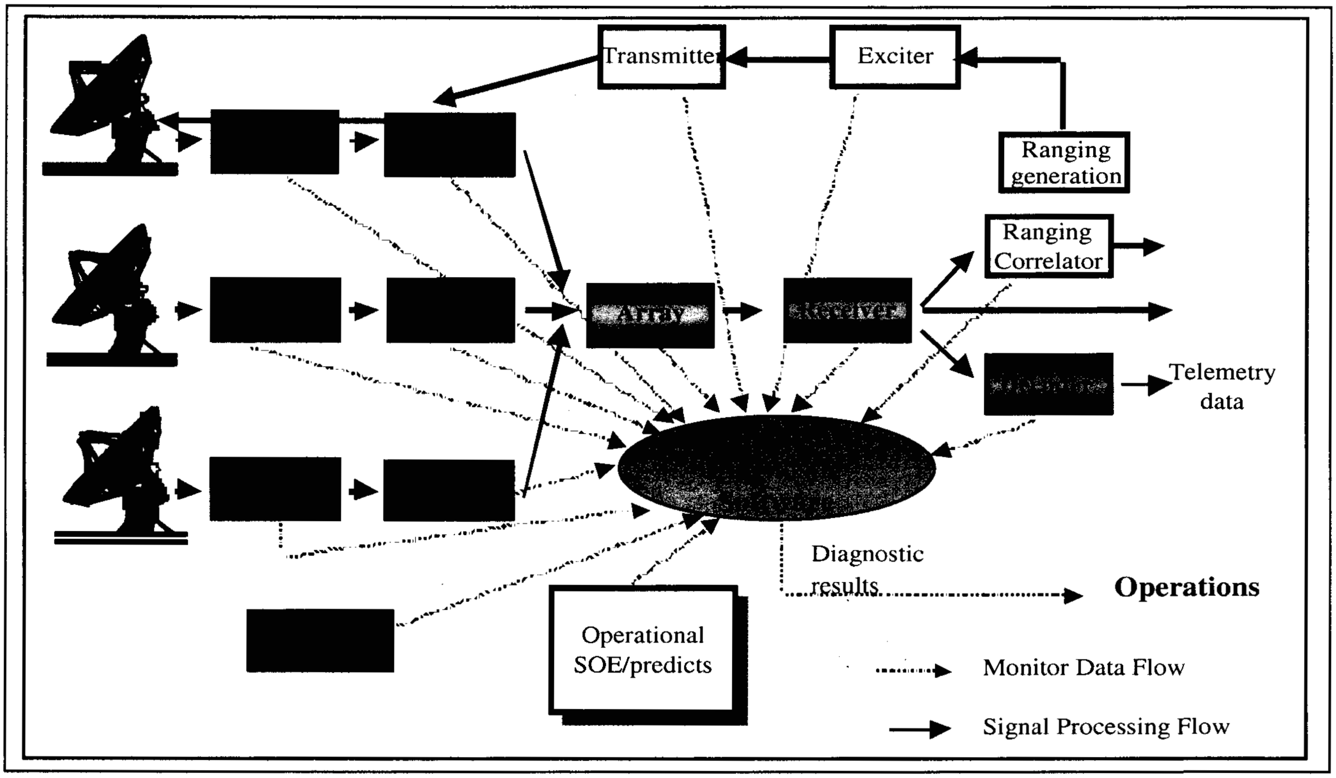

Figure 1: Block Diagram of DSN Hardware Configuration

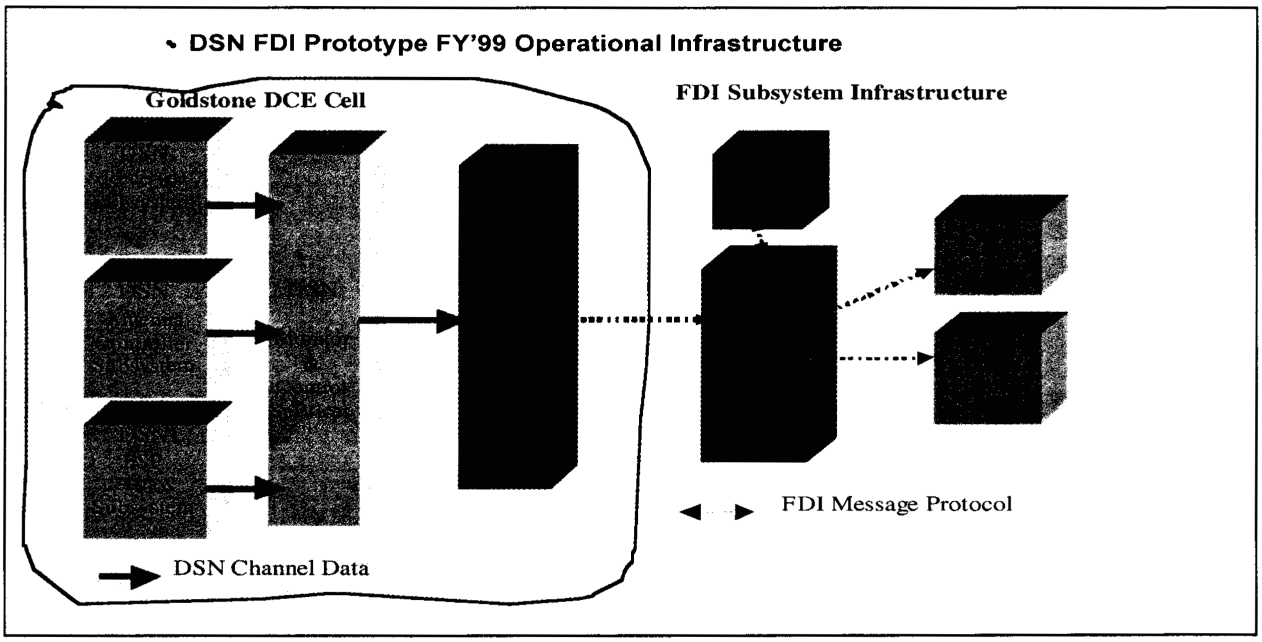

Figure 2: DSN FDIR Prototype FY'99 Operational Infrastructure

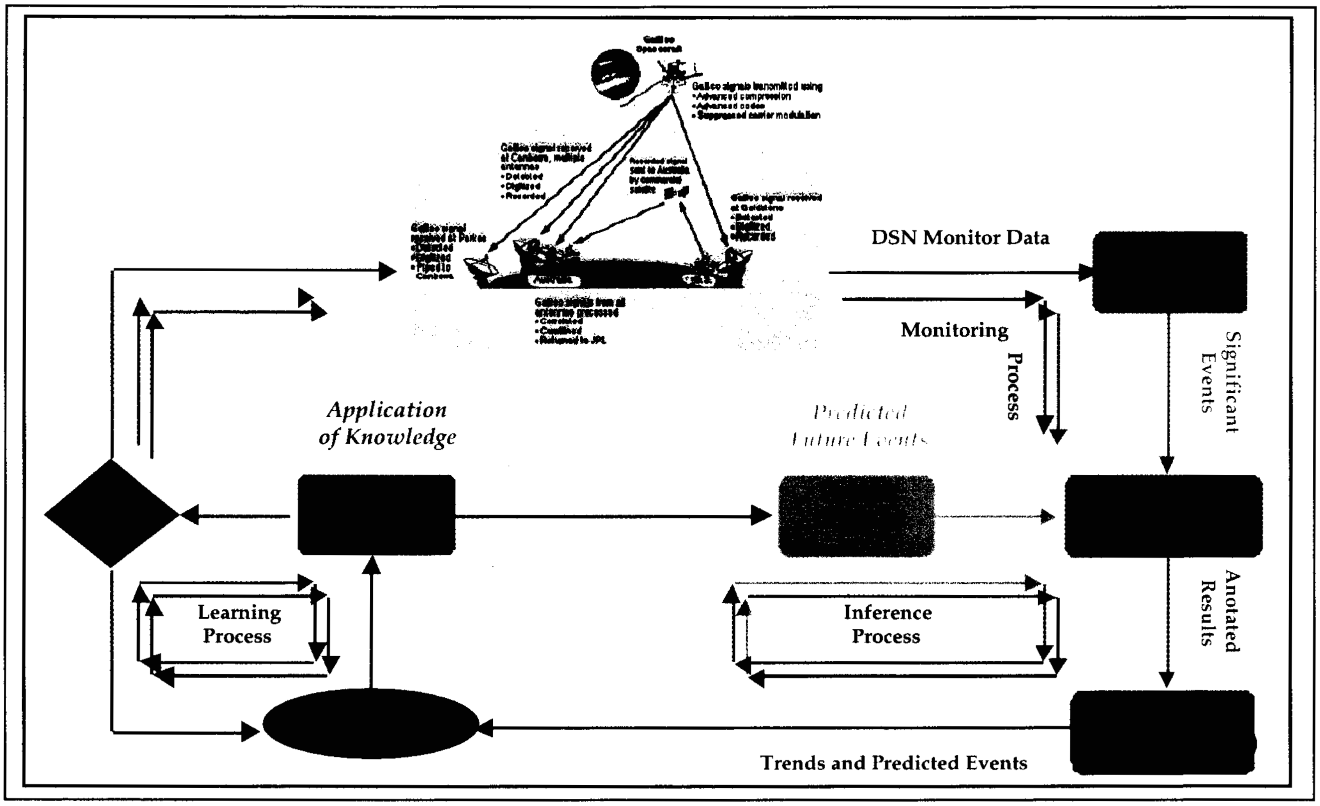

Figure 3: FDIR BEAM and SHINE 2000 Architecture

The FDI Server software adheres to the DSN's standards and protocols for data exchange. The FDI Server isolates tools such as SHINE and BEAM from the intricacies of DSN interface requirements. The SHINE-based expert system's rule-base has been built incrementally with heuristic knowledge imparted by a DSN array expert. The SHINE inference engine is currently using CMU-LISP and dynamically links in the FDI communications wrapper. The FDI-BEAM client application consists of the core BEAM computational engine with the FDI wrapper. Both the FDI Server and the BEAM client application have been prototyped using C. All diagnostic output is handled by a JAVA-based GUI.

Our FDI framework allows the expert system and BEAM client to continuously process DSN monitor data and predicts, and to generate diagnostics in a real-time environment. The automation that has been introduced is in the analysis and diagnosis based on monitor data and predicted behavior. Currently, during spacecraft tracking operations, an operator must look at many displays of monitor data. From past experience, the operator focuses on changes in specific channels of data to determine if a problem exists. Our system has the ability to continuously process all monitor data, quantify monitor data contribution to system health, identify data signatures associated with nominal conditions, and detect and isolate anomalous events in an autonomous manner.

DISCUSSION OF BEAM

Beacon-based Exception Analysis for Multi-missions (BEAM) presents a fundamentally alternate onboard technology for aircraft health assessment, prognostics and increased predictability in autonomic logistics. The technology is grounded in a radical approach to complex systems analysis, combining advances in adaptive wavelet theory, nonlinear information filtering (NIF), neuro-fuzzy system identification and stochastic modeling. An essential component of BEAM is a new real-time high-fidelity algorithm that can robustly and compactly analyze complete spacecraft state from an information-theoretic standpoint, thus enabling unattended space flight for days and months. The NASA relevance lies in the ability to provide accurate system health and wear assessment on demand.

BEAM provides a new real-time, in-situ method to:

1. Fuse and simultaneously analyze all system observables such as sensor data, executing software, commands, etc.
2. Automatically abstracts system physics and information invariants notwithstanding model availability and fidelity.
3. Ultra-sensitive to degradation/changes in the system detect and isolate changes in both space and time.
4. Highly scaleable and runs on conventional processors.

Figure 4 above represents a notional application of BEAM onboard a spacecraft or aircraft, to provide a complete health and state assessment.

From an algorithmic standpoint, BEAM provides an extremely formal and robust approach to predictive aircraft analysis at the systems level, and goes well beyond traditional redlining and trending filters endemic to telemetry-based monitoring systems.

BEAM entails three components:

1. An on-board sensor fusion operator.
2. A hypercompact operating map, computed on board and then downlinked, which encapsulates hours, days or weeks of state information and PHM assessment.
3. A backprojection operator that provides causal interpretation of events on the ground, time-to-criticality and wear-assessment for the purposes of scheduling maintenance activities.

A block diagram of the components of BEAM can be seen in figure 7. The theoretical foundation in which BEAM is based is beyond the scope of this paper and is discussed elsewhere.

Inputs to BEAM vary depending upon the specific subsystem. Inputs may contain raw sensor information, command variables, software variables, performance metrics if any, global variables that pertain to system mode and state and list of critical observables for each mode, determined a priori.

The output essentially provides all information necessary to detect and isolate the failure with high confidence.

The value of anomaly detection will then depend upon:

- The accuracy of the conclusion.
- Confidence in the conclusion.
- Timing of the detection.
- Correct isolation of contributing signals.

BEAM processes data a frame at a time. A frame is defined as a collection of data that was all sampled at the same time. Each frame is composed of channels where each channel is defined as a particular piece of data. Channels are predefined and held constant across all frames but their values may vary from frame to frame. For each frame, the channels are ranked according to their degree of contribution.

BEAM generates the following information for each frame of data that it processes:

1. Time of anomaly
2. Ranked listing of channels
3. Confidence Ratio (distance / variation threshold)
4. Time of return to nominal

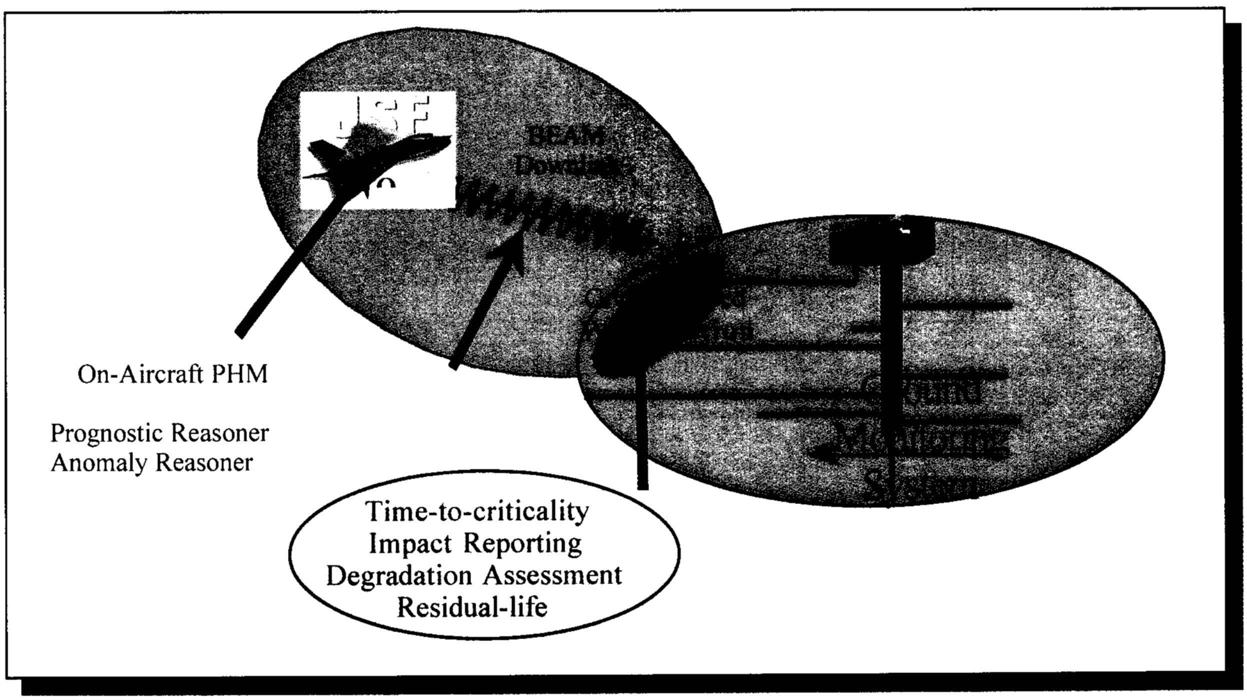

Figure 4: BEAM Technology Application for NASA Onboard Analysis

DISCUSSION OF SHINE

SHINE is a reusable inference engine for the monitoring, analysis and diagnosis of real-time and non-real-time systems. It is a system developed at NASA to meet many of their demanding and rigorous AI goals for current and future needs. It is a system that was designed to be efficient enough to operate in a real-time environment and to be utilized by non-LISP applications written in conventional programming languages such as ADA, C, Fortran and Pascal. These non-LISP applications can be running in a distributed computing environment on remote computers or on a computer that supports multiple programming languages.

Knowledge-based systems for automated task planning, monitoring, diagnosis and other applications require a variety of software modules based on artificial intelligence concepts and advanced programming techniques. The design and implementation of the modules require considerable programming talent and time and background in theoretical artificial intelligence. Sophisticated software development tools that can speed the research and development of new artificial intelligence applications are highly desirable. The SHINE system was developed for that purpose. Included in the system are facilities for developing reasoning processes, memory-data structures and knowledge bases, blackboard systems and spontaneous computation daemons.

SHINE is a multi-mission reusable knowledge base software tool for monitoring, analysis and diagnosis of spacecraft and ground systems through forward and backward inferencing.

SHINE advances the state-of-the art in artificial intelligence by enabling solutions to a broad class of problems that previously were considered intractable because real-time system requirements, high-speed real-time and small size constraints, portability or flight hardware ready availability.

SHINE introduces a novel paradigm for knowledge visualization and ultra-fast inferencing that goes well beyond traditional forward and backward chaining methodology. A sophisticated mathematical transformation based on graph-theoretic data flow-analysis is introduced, that reduces the complexity of conflict-resolution during the match cycle from $O(n^2)$ to $O(n)$ for many kinds of pattern matching operations. Computational overhead is further minimized by the in-built source-to-source transformational system for the optimization of code generated from the rules through data flow reduction.

The development of SHINE is the based upon the experience and requirements and experience that were collected over the years by the Artificial Intelligence Research group at JPL in developing expert systems for the diagnosis of spacecraft health. Computational efficiency and high performance are especially critical in artificial intelligence software. That consideration has been an important objective for the SHINE system and has led to its design as a toolbox of AI facilities that may be used independently or collectively in the development of knowledge-based systems.

SHINE provides over 1,000X increasing in inference speed and up to 10,000X reduction in execution environment, over the best comparable commercial product. SHINE's unique approach to knowledge representation, knowledge-visualization and reasoning processes, enables any developer to build high-performance expert systems, previously only within the reach of "AI experts".

It is intended for those areas of inferencing where speed, portability and reuse is of critical importance. Such areas would include spacecraft monitoring, control and health, telecommunication analysis, medical analysis, finical and stock market analysis, fraud detection (e.g. banking and credit cards), robotics or basically any area where rapid and immediate response to high-speed and rapidly changing data is required.

SHINE comprises of a collection of high-level software tools that revolutionizes the creation of efficient, reusable knowledge-based software systems. Unlike existing expert systems, SHINE generates only application-critical code, thereby eliminating the need to deploy the complete environment. SHINE's unique approach to the creation of knowledge-based systems is based on sophisticated compiler technology, one of the fastest inference engine in the industry, and a large library of AI problem-solving techniques, please see figure 5.

SHINE provides ultra computing performance on desktops computers that were previously not even available on large mainframe systems. For ease of use and broad-spectrum applicability it directly interfaces with applications written in C, C++, ADA, FORTRAN, ALGOL and LISP and generates native code for C, C++ and LISP. With targets planned for ADA, BASIC and FORTRAN.

SHINE has contributed to reduced operations cost, improved reliability and safety in eight NASA deep space missions that include Voyager, Galileo, Magellan, Cassini and Extreme Ultraviolet Explorer (EUVE). It is a prototype operational system for the Deep Space Network. SHINE has been delivered to the NASA's X-33 as a flight system component of JPL's Avionics Flight Experiment (AFE) and will be flown in 2000.

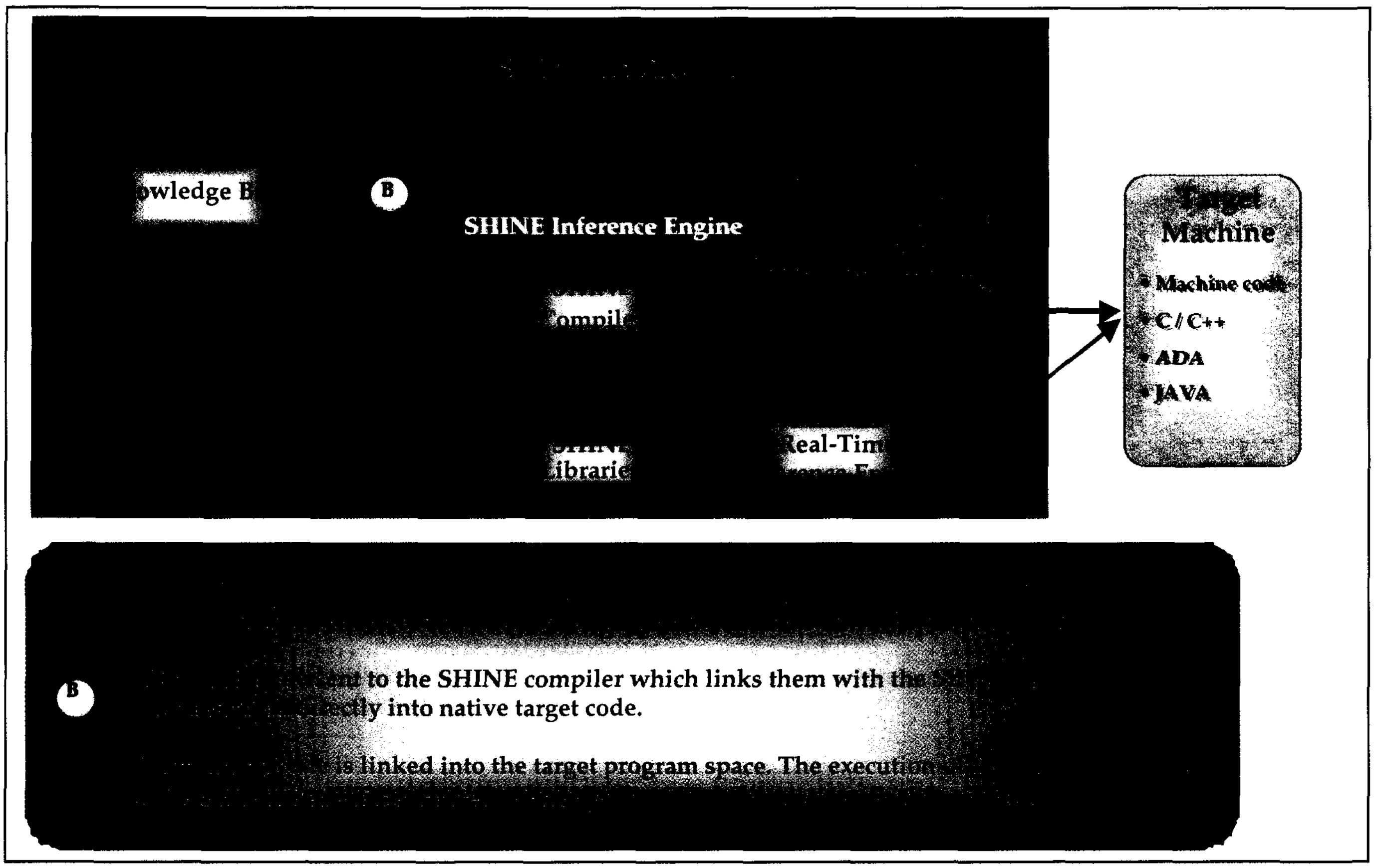

Figure 5: SHINE Architecture

BEAM & SHINE IN DSN OPERATIONS

The '99 FDI antenna array prototype (Figure 6) successfully demonstrated: 1) Autonomous monitoring of downlink signal processing using DSN predicts and telemetry channel data; 2) Detection of anomalies based on SNR channel data analysis; and 3) Identification of DSN channel contribution to significant system behavior changes.

In our '99 work, we used BEAM to provide a framework of fault tolerance for key tracking observables such as signal to noise ratios and range frequencies. BEAM was also used as a prognostic tool by indicating when the system was deviating from the nominal performance requirements. It detected faults in parallel with the expert system. Our BEAM output consists of: 1) A normage value which is an instantaneous estimate of the system as a single even-based metric of system health; 2) A normage limit which is an instantaneous estimate of the system threshold; 3) A DSN channel ranked list which identified the channels associated with significant system behavior; and 4) An Operating map which is a summarization of the system channel behavior and provides a means of dynamic system state visualization.

The expert system performed further fault identification and isolation using heuristic knowledge. Forward chaining rules were used to define semantics of FDI messages and to analyze telemetry frame data. Each data item is associated with 1 or more hypotheses that are generated as data arrives. Backward chaining rules were used to resolve all ambiguities in the hypotheses generated during telemetry frame collection. Model-based reasoning was used to combine real-time channel data with conclusions generated by the backward reasoning phase, and to map conclusions to actual hardware configuration.

The above is depicted in Figures 8 and 9. Figure 8 shows how the expert system and BEAM simultaneously detected an anomaly. The output in Figure 9 was produced in real-time. The FDI Subsystem participated in a DSN tracking of Near Earth Asteroid Rendezvous (NEAR) mission using the new FSP Array Subsystem at the Goldstone Deep Space Communications Complex.

CONCLUSIONS

Just as artificial intelligence can play an important role in the monitoring and diagnosis of mission operations, the tools that are used to develop these systems also plays an important role. This is especially true when issues of reliability, real-time performance, limited code and execution size, easy of use and maintainability are all factored in.

The AI techniques and tools that were developed for the DSN are well suited for the monitoring and diagnosis of ground systems in general. Both BEAM and SHINE run well in environments where system resources such as processor cycles and memory are at a premium. Both of these systems have been demonstrated in stand-alone advisory systems for human operators as well as components of embedded systems. Both of the tools generate C++ code that allows them to run efficiently in flight systems with real-time operating systems such as VxWorks.

The benefits afforded by the application of these tools and techniques are significant. The architecture and autonomous fault diagnosis techniques pioneered in the SHARP[5][6][7] system have demonstrated important benefits for operator productivity and spacecraft safety and have the potential to reduce workforce requirements for future space operations.

No matter how good your tools are, knowledge acquisition remains a fundamental bottleneck for development of applications of these systems and for knowledge-base systems at large.

The ultimate goal of the DSN automation effort is "lights out" operations in order to achieve significant cost reduction. The lights, however, must be dimmed gradually. The DSN FDI Automation work described in this paper has taken the first steps toward the dimming process. Another important aspect of our work is that of technology infusion into DSN operations. We have created a prototype that exercises innovative BEAM and SHINE technology in the conservative DSN operational environment. The ability to analyze all system data and perform system health assessment at all levels of operations is key in achieving autonomous reasoning and autonomous decision-making.

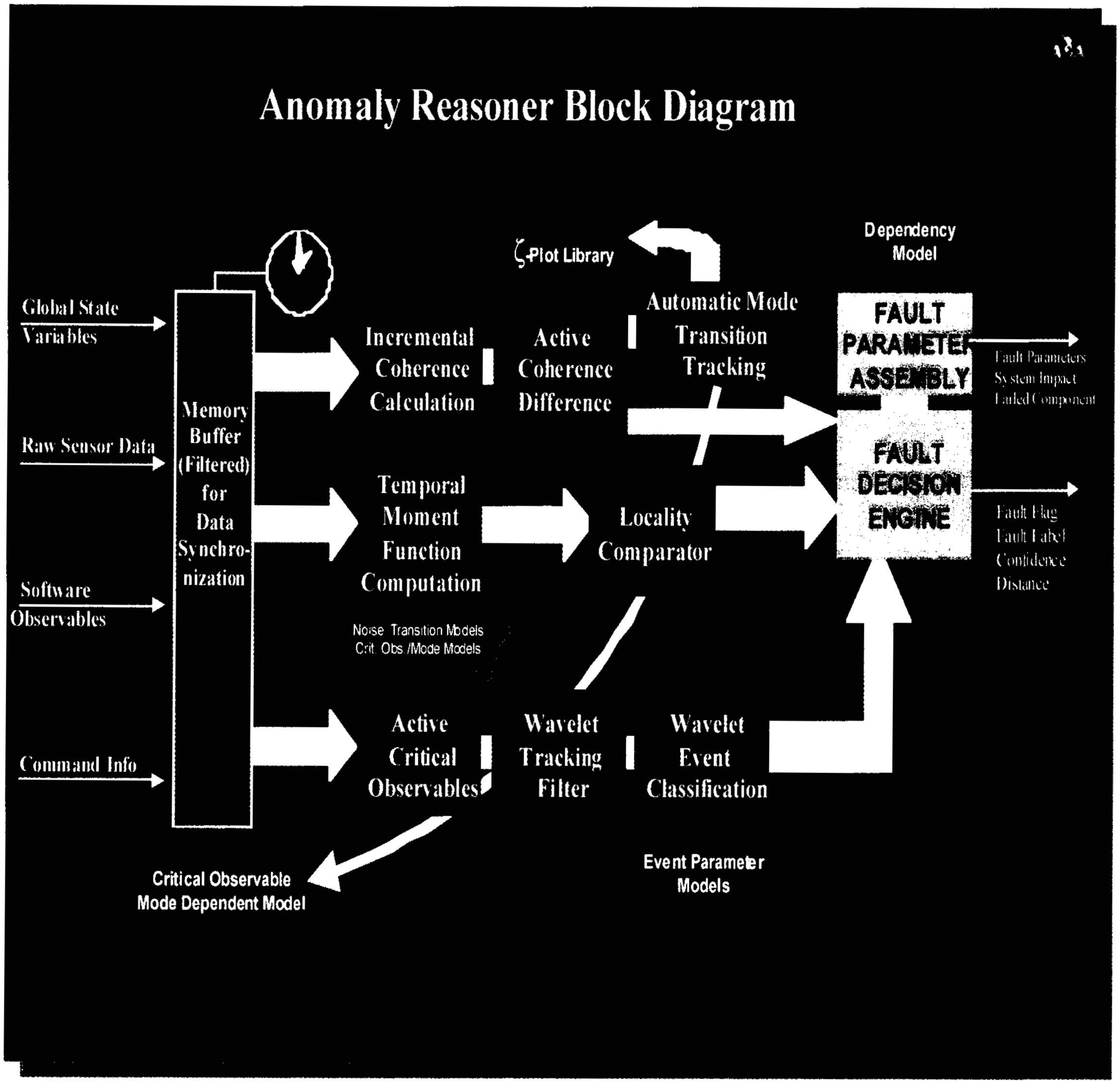

Figure 6: Overview Schematic for Anomaly Reasoner

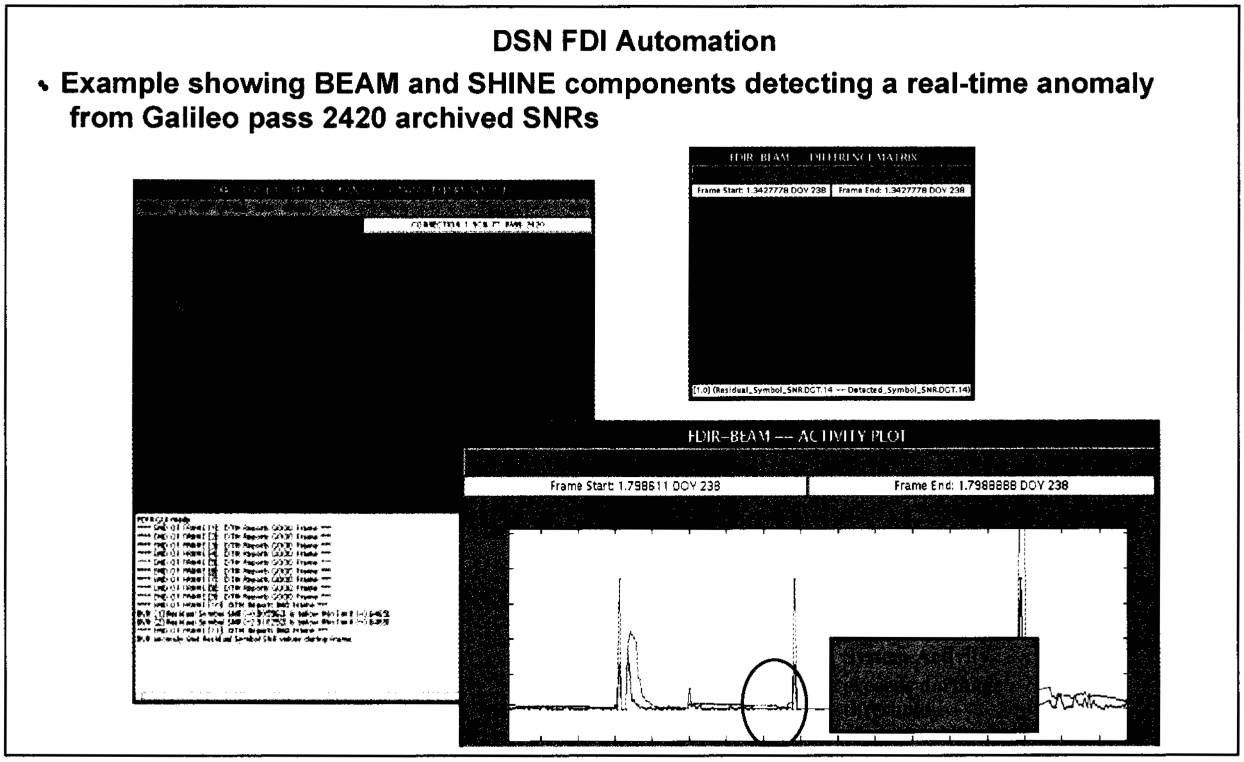

Figure 7: BEAM and SHINE Detecting a Real-Time Anomaly

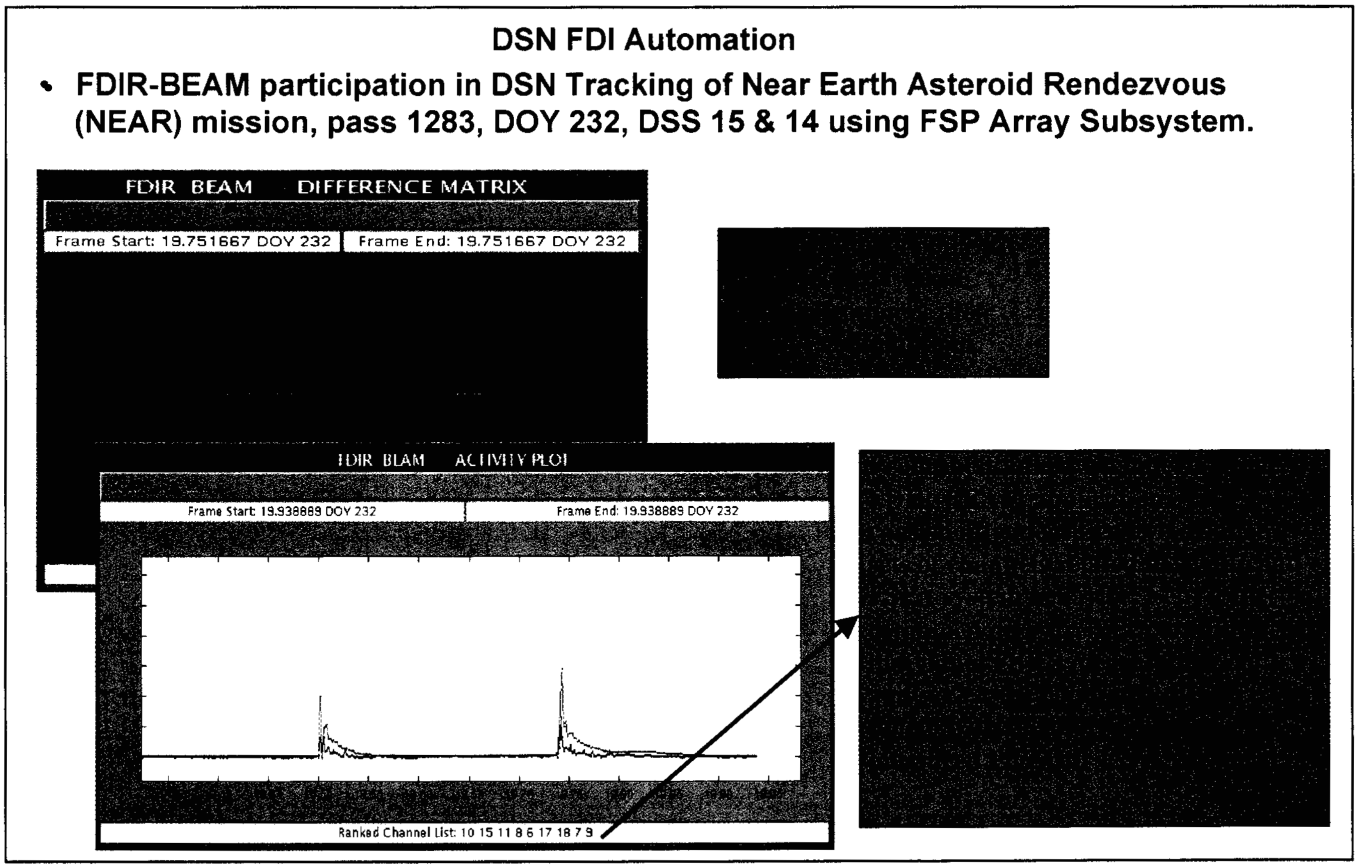

Figure 8: BEAM and SHINE Detecting a Real-Time Anomaly

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13. Biography

Mark L. James is a Senior Member of the Technical Staff in the Ultracomputing Technologies Research Group in the Information and Computing Technologies Research Section within NASA's Jet Propulsion Laboratory, Pasadena, CA. At JPL Mark is Principal Investigator and Task Manager on a world class program in real-time inferencing and knowledge-based systems. He manages a number of JPL and NASA software projects. His primary research focus is on high-speed inference systems and their application to planetary and deep spacecraft systems, and, medical applications. His expertise includes core artificial intelligence technology, high-speed real-time inferencing systems, flight system software architectures and software design and implementation for those systems; image processing and scene analysis; pattern recognition, planning and simulation; real-time control systems, programming languages and compilers; symbolic mathematics, operating systems, hypermedia systems, AI programming environments, robotics, visual programming and virtual reality systems. Additional expertise in medicine, biology and analog and digital electronics design. Mark has received a number of NASA awards which include: NASA Software of the Year Award Nominee for 1997 and 1998, JPL Team Excellence Award for 1990, JPL JET Productivity Award for 1990, Major NASA Monetary Award for 1990, NASA Certificate of Recognition for 1990, NASA Achievement Award for 1990, NASA Exceptional Service Medal for 1989, NASA Exceptional Service Plaque for 1989 and NASA Manned Flight Awareness Nominee for 1988 and 1989.

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